NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

May 1943 as
Advance Restricted Report 3E21

TESTS OF EXHAUST PROPULSION NOZZLES

By Paul J. Campbell
United Aircraft Corporation

194

NACA

WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

TESTS OF EXHAUST PROPULSION NOZZLES

By Paul J. Campbell

SUMMARY

The thrust produced by a variety of exhaust stacks and nozzles, and the effect of these stacks and nozzles on the power of a single-cylinder R-2800 engine were investigated over a wide range of engine speeds and manifold pressures in a series of tests in the Pratt & Whitney experimental test department. From the data obtained it is possible to estimate the optimum form of nozzles and the available thrust for airplanes fitted with R-2800 engines under sea-level conditions.

APPARATUS

The apparatus is shown in figure 1. The mean thrust of the exhaust gas on the engine was measured indirectly as a force in the opposite direction against a swinging target. The mean force against the target was balanced by positioning a weight on a horizontal arm, keyed to the shaft from which the target was suspended. The position of the weight was thus a measure of the thrust. The target and arm were supported on ball bearings.

The target was designed on the basis of previous experience with targets on compressed air nozzles. Unless the jet is dispersed within the target, the entire flow tends to leave at the rear, and air is actually drawn in through the remaining spaces, causing the target to indicate more than the true reaction. To avoid this error, the target was provided with an internal cup-shape baffle as shown in figure 1. Calibrations with compressed air over a range of flows from zero to more than three times the maximum engine exhaust flow proved that the design was satisfactory. Later, observations of flames leaving the target indicated that gases left the target uniformly and at substantially right angles to it.

The target was enclosed in a 26-cubic-foot water-jacketed chamber, where the exhaust gas was cooled by sprays of water before being discharged through the roof. The top of this chamber was provided with ways so that the target could be located at various distances from the cylinder.

The testing was done on the S-19 2800 single-cylinder engine, mounted on the X-42 eddy-current dynamometer. Engine parts of particular importance to these were as follows:

Cylinder	57708	Nominal timing of cam:	
Piston	34254 and 37851	Intake opens	20° B.T.C.
Cam	8363	Intake closes	76° A.B.C.
		Exhaust opens	76° B.B.C.
Compression ratio was 6.7		Exhaust closes	20° A.T.C.
Spark advance was 20°			

Engine accessories were similar to those usually used for single-cylinder testing by Pratt & Whitney. Combustion air was supplied from the factory compressors through a reducing valve, a Roots meter, and an electric heater. Fuel and water consumption were measured by rotameters.

The exhaust nozzles were machined of steel. The various shapes of exhaust stacks were built up from sheet steel and steel tubing. These are all shown in figure 2. The entrance of all stacks and nozzles was the same diameter as the exhaust port of the cylinder. The area of this port was 4.67 square inches.

METHOD

In order to find whether the target would measure accurately the thrust due to a jet, it was first calibrated with a continuous jet of air. Both the intake and the exhaust valves were blocked open and, with the engine not running, air was blown through the cylinder and nozzle into the target. Temperature and total pressure were measured in the pipe ahead of the nozzle. From these measurements and the flow of air through the Roots meter, it was possible to calculate the thrust of the jet. It was found that the thrust indicated by the target was about 95 percent of the theoretical. No method was available for making a similar check with discontinuous flow, so that it was necessary to assume that the target would indicate the mean of a pulsating force with equal accuracy.

When making the tests, the engine was run at constant speed and the intake-port pressure was varied from 30 inches of mercury absolute to the detonation limit for pursuit grade fuel. Conditions of operation were as follows:

Engine speed, rpm	1500	2550	2700
Fuel-air ratio	0.065	0.085	0.085
Intake-air temperature, °F	200	200	200
Rear spark-plug temperature, °F . . .	450	500	500

The tests covered a period from July 25, to November 10, 1942.

ANALYSIS OF RESULTS

Thrust against Nozzle Area and Stack Length

The exhaust gas thrusts for various combinations of nozzles and straight exhaust stacks are shown in figures 3 to 12. These curves cover a range of speeds from 1500 to 2700 rpm, and a range of intake-port pressures from 30 to 57 inches of mercury absolute.

It is apparent from these figures that the thrust may be increased by reducing the exit area of the nozzle. However, if the nozzle area is made extremely small, the thrust may be decreased because of reduced air consumption of the engine. This effect is greater at high engine power and does not appear at all in the runs at 1500 rpm.

The thrust is more sensitive to variations of nozzle area when the exhaust pipe is short. For example, compare figures 3 and 8 for pipe lengths of 14 and 50 inches, respectively. If the pipe exit is not restricted (4.67 sq. in.), the long pipe produces a greater thrust. As the exit area is decreased, the thrust of the long pipe increases very little and finally falls off at an exit area of 1 square inch. The thrust of the short pipe, however, increases rapidly as the exit area is decreased and rises above the thrust of the long pipe. This trend is shown differently as curves of thrust against stack length in figures 11 and 12. Here it is apparent that increasing the stack length causes an increase in thrust if the exit area is large - a decrease in thrust if the exit area is small.

Engine Power against Nozzle Area and Stack Length

Figures 3 to 12 also contain plots of engine power. It is evident that when the nozzle area is reduced below a certain value, a serious loss of engine power results. This critical value of nozzle area depends on the engine speed and intake-port pressure and, probably, on the back pressure. At 1500 rpm and 30 inches of mercury intake-port pressure (figs. 5 and 10), the critical area is evidently less than 1 square inch. At 2550 rpm and 30 inches of mercury (figs. 4, 7, and 9) the critical area is about 3 square inches. Of particular importance, however, is the fact that for running at 2700 rpm at intake-port pressures above 40 inches of mercury, the critical area is evidently greater than the area of the unrestricted stack (figs. 3, 6, and 8). At these values of engine power, any reduction whatever of exit area causes appreciable power loss.

The effect of exit area on power is also related to the length of pipe between the cylinder and nozzle. In figures 11 and 12, the following trends may be observed: If the exit is not restricted, the length of pipe (up to 50 in.) has no effect on power. When the exit area is moderately reduced, there is a critical length of pipe above which power drops rapidly. This critical length is much more apparent when engine power is high. If the exit area is made extremely small, the effect of length is reversed; that is, power increases with increasing length.

Tests of Various Shapes of Stacks

In addition to straight stacks with nozzles at the exit, a number of other shapes were tested.

Branched stacks. - It is usually impossible in an airplane to provide as many exhaust outlets as there are cylinders. Consequently, it is customary to connect the exhaust pipes from alternately discharging cylinders into a common outlet. To simulate this practice, tests were made of a number of branched pipes to determine their effect on power and thrust. These pipes are shown in figure 2. The added branches were closed at the end to simulate the closed exhaust valve of the alternately discharging cylinder. The results are shown in figure 13. The effect on thrust was negligible. The effect on power, however, was a slight, but consistent increase for stacks 2 and 3. When the branched stacks were replaced with a short single stack the power dropped back to its original value. There is apparently some quality about branched pipes which gives a slight power increase. It may be that a column of gas is compressed in the branch during the first part of the discharge period, which later acts as the primary fluid in an ejector to suck gas out of the cylinder during the latter part of the period. Whether or not the presence of an alternately discharging cylinder would change the results is not known. There can be little doubt that thrust would be doubled when two nonoverlapping cylinders are connected to one outlet. At least, it seems likely that branched stacks attached to nonoverlapping cylinders of an engine would not be detrimental either to power or to thrust.

Long restrictions. - An exhaust pipe, restricted for most of its length, has been recommended as a flame suppressor. Although flame observations in this apparatus were meaningless because of the presence of the target, two of this type of pipe were tested for their effect on thrust and power. These pipes are shown in figure 2. In each, the restriction extended from a point 8-3/4 inches from the cylinder to the exit, 50 inches from the cylinder. The results are shown in figure 14. The effect on power was about the same as the effect of a nozzle of the same area at the end of a 2.44-inch-diameter pipe. The thrust, however, was increased appreciably. This increase does not seem logical, but it was observed consistently over a wide range of intake-port pressures.

Diffusing pipe. - On many of the Rolls-Royce installations the exhaust gas passes through an enlarged chamber before entering the nozzles. A similar arrangement was tested in this apparatus. It was made in the form of a gradually expanding section, followed by the nozzle. (See fig. 2.) The results are shown in figure 13. The effect on thrust was negligible. The power, however, appears to have been slightly increased.

Water injection. - The effect on thrust of injecting water into the intake was determined for one of the long-throat nozzles. Water was injected continuously into the intake pipe through a spray nozzle at a rate equal to 35 percent of the fuel rate. Other running conditions were not changed. The results are shown in figure 15. It will be seen that the addition of water caused a slight loss of power, at the same manifold pressure, and a slight increase in thrust. The thrust obtained in this run was remarkably high, reaching a maximum of 29 pounds at the detonation limit. The increase in thrust was greater than the increase in mass flow, due to the addition of water.

GENERAL DISCUSSION

Selection of nozzle size. - Exhaust nozzles should be designed so that the total thrust power delivered by the propeller and exhaust gas is a maximum. The design condition will usually be level flight at critical altitude at normal or military power. If only this one flight condition is considered, it will often appear desirable, especially at normal power, to restrict the exit in order to gain in exhaust gas thrust at the sacrifice of little or no propeller power.

However, if the nozzle area is chosen on this basis, the airplane performance may be seriously impaired at lower speeds at military power, such as in take-off and climb. Therefore, it is necessary to compromise in the area of the nozzles. These tests indicate that the best compromise will usually be no restriction whatever at the stack exit. This conclusion is particularly applicable to long exhaust stacks, where the gain in thrust due to a reduction of area could not offset the loss of engine power at military rating, even at high speed.

Power increase due to exhaust thrust. - The power which the exhaust-gas thrust delivers to the airplane is simply the product of the thrust and the airplane velocity. For example, an unrestricted stack 50 inches long produces a thrust of 15.6 pounds at sea level at military power (fig. 8), or 280 pounds for the multicylinder engine. At 400 miles per hour, this thrust would produce 300 horsepower. No engine power has been lost, so that the net gain in thrust power is 300 horsepower. If propeller efficiency is 80 percent, and the engine is delivering 2000 horsepower, the net gain is 18 percent. Much greater gains may be expected at altitude.

Back Pressure

The exhaust back pressure, as measured by a manometer connected to an exhaust pipe near a cylinder, has been used as a standard in the design of collectors and for comparing engine-power losses. There are two reasons why this measurement should not be used. First, it is generally impossible to measure the mean of a rapidly varying pressure with a manometer. In previous tests made by the United Aircraft Corporation (Rep. R-54, Feb. 1941), a manometer measurement of mean exhaust pressure was compared with the true mean obtained by integrating an indicator card; the error was over 700 percent. Second, even if the manometer did indicate the true mean, it still would be a poor criterion for comparing engine power losses because the power loss depends on the back pressure during the last part of the exhaust stroke, and not on the mean pressure.

Back pressures were measured in these tests in the customary manner by a mercury manometer connected to the exhaust pipe near the cylinder. Some of the results are shown in figure 16. It will be observed that the same power loss or thrust may be obtained at many different values of back pressure, depending on the size and shape of the exhaust stack. Conversely, a given value of back pressure may correspond to widely different values of thrust and power loss for different stacks. For example, at a back pressure of 1.6 inches of mercury, the power loss is zero for the 50-inch stack with no restriction, and 5 percent for the 14-inch stack with an exit area of 2.9 square inches. The respective thrusts are 15.6 pounds and 17.0 pounds.

Parameters

In reference 1 it was possible to correlate a large number of test points for various nozzles, engine speeds, intake-port pressures, and exhaust pressures by the use of two parameters whose units are feet per second. These parameters are:

Mean exhaust-gas jet velocity $\overline{V}_c$, and the function $\dfrac{p_o A}{M_c}$

$\overline{V}_c$ thrust/(mass flow of exhaust), feet per second

p_o atmospheric pressure, pounds per square foot

A nozzle area, square feet

M_e mass flow of exhaust, slugs per second

The mean exhaust-gas jet velocity represents the equivalent steady velocity which would produce the observed thrust at the same mass flow. The second parameter is the reciprocal of the expression for velocity in the continuity equation (with the addition of gravity and the omission of temperature and the gas constant). When these parameters were plotted against each other, the points in reference 1 all fell on a smooth curve.

When the data from the Pratt & Whitney tests are plotted in this way, the points for different lengths of exhaust pipe should fall on separate curves because of the observed differences in thrust. Plots are shown in figures 17 and 18 for pipe lengths of 14 inches and 50 inches, respectively. The plotted points cover speeds from 1500 to 2700 rpm, and intake-port pressures from 30 to 57 inches of mercury absolute. The points for the respective pipe lengths will be seen to fall fairly near two separate curves, similar to the curve in reference 1. If individual curves are drawn through the data for each speed and nozzle, it will be observed that most of them cross the mean curve. At high powers they even tend to hook and reverse their direction. The direction in which they cross the mean curve evidently depends on the length of pipe. The individual curves for the 14-inch pipe tend to be more nearly horizontal than the mean curve; for the 50-inch pipe they are more nearly vertical. The fact that the tests of reference 1 were made with an intermediate length of pipe may explain why better correlation was found.

The value of a plot of this type is that it enables the user to determine the thrust for given values of nozzle area, altitude pressure, and exhaust mass flow. However, until it is confirmed by more extensive testing, it should be used with caution for extreme conditions. In reference 1 excellent correlation was found at low engine power and at exhaust pressures from 30 to 12 inches of mercury absolute. The Pratt & Whitney tests at sea-level exhaust pressure and high engine power give only fair correlation. Just how well these curves would represent the thrust at low exhaust pressure and high engine power remains to be learned.

CONCLUSIONS

1. The thrust produced by an exhaust nozzle for given engine-operating conditions depends on its exit area, the length of pipe between the cylinder and nozzle, and on the length of the reduced-area section of the nozzle.

2. The effect of an exhaust nozzle on engine power depends on its exit area and the length of pipe between the cylinder and nozzle.

3. By a proper choice of exhaust-pipe length and nozzle size, it is possible to produce a force equivalent to a continuous thrust of approximately 16 pounds per cylinder at the present military rating of the R-2800 engine at sea level without any loss in engine power. At 400 miles per hour, this amounts to 300 horsepower. Greater thrusts may be expected at altitude.

4. In general, restricting the stack outlet does not appear to be advisable because of the adverse effect on take-off power.

5. At a given manifold pressure, the injection of water into the intake pipe causes a slight increase in exhaust gas thrust.

6. The practice of joining exhaust stacks from non-overlapping cylinders into a common exit appears to be entirely satisfactory. There is some evidence that this system may actually increase engine power.

7. The mean exhaust back pressure, as measured by a manometer in an individual stack, does not determine either the thrust or the engine power loss.

RECOMMENDATIONS

Since the only available data for predicting exhaust thrust and power loss at altitude are based on tests of a Wright 1820 cylinder at low specific output (reference 1), it is recommended that tests of an R-2800 cylinder at high specific output be conducted under altitude conditions, similar to the sea-level tests reported herein.

Research Division,
United Aircraft Corporation,
East Hartford, Conn.

REFERENCE

1. Pinkel, Benjamin, Turner, L. Richard, and Voss, Fred: Design of Nozzles for the Individual Cylinder Exhaust Jet Propulsion System. NACA ACR, April 1941.

W-43

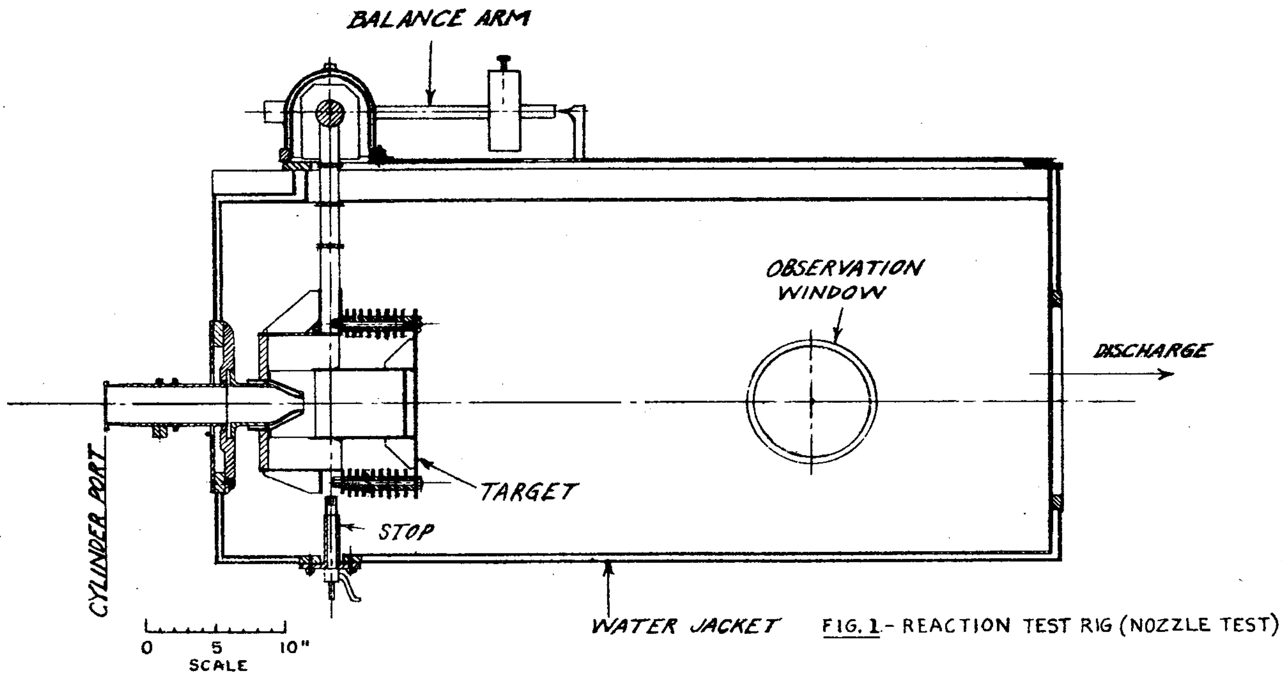
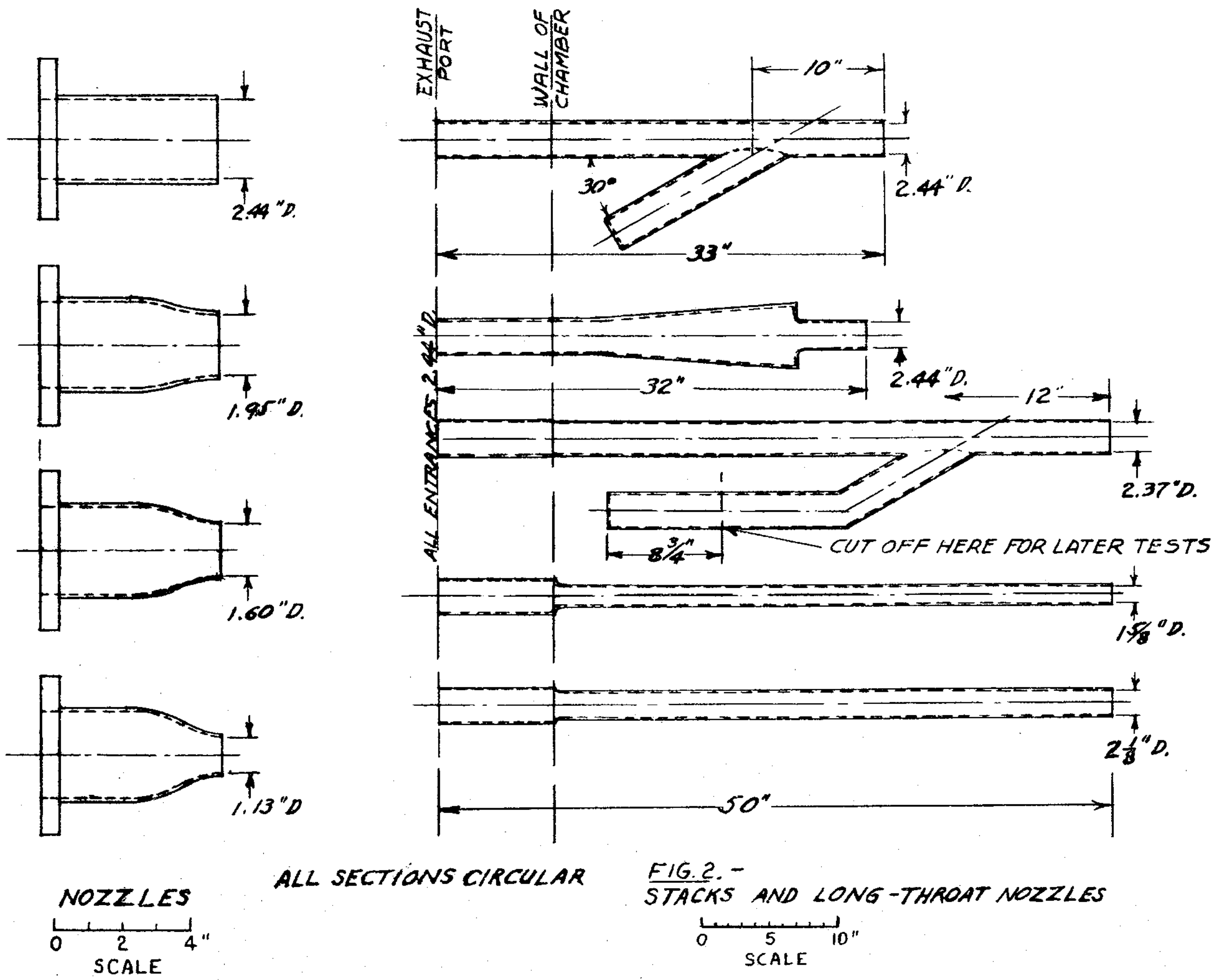


FIG. 1 - REACTION TEST RIG (NOZZLE TEST)



ALL SECTIONS CIRCULAR

FIG. 2. - STACKS AND LONG-THROAT NOZZLES

W-43

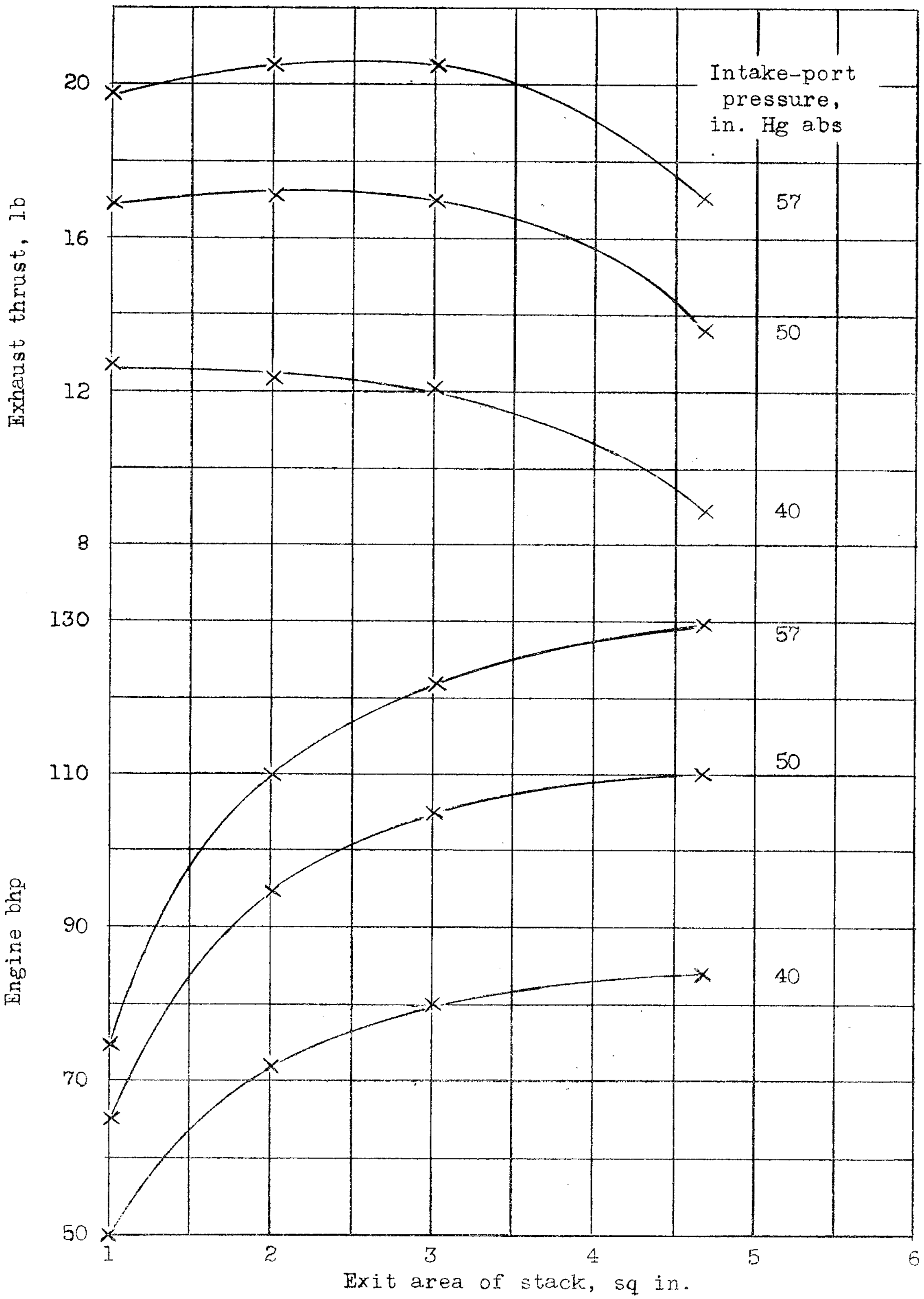


Figure 3.- Effect of stack area. Total exhaust-stack length, 14 in.; engine rpm, 2700; restriction at exit; fuel/air, .085.

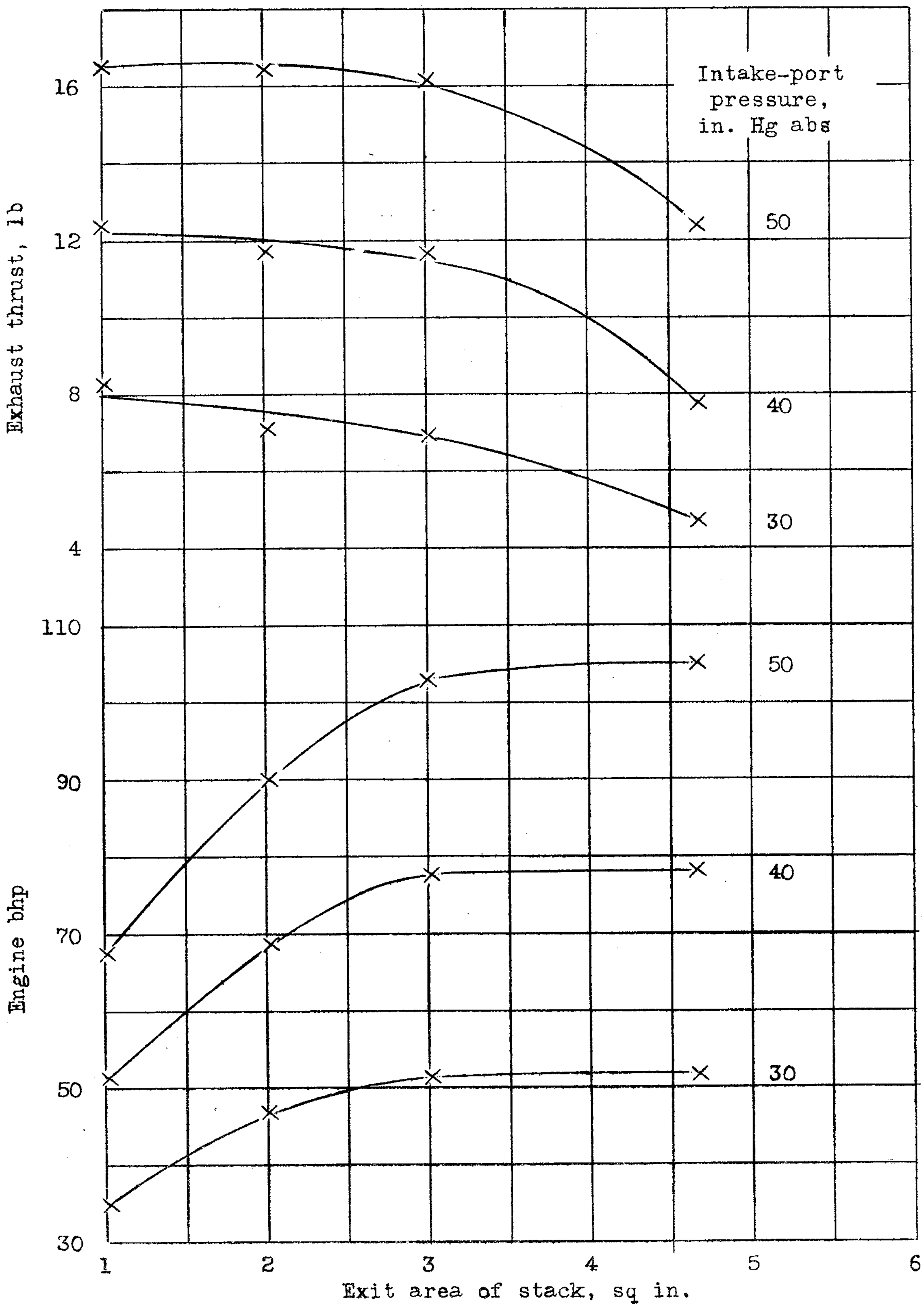


Figure 4.- Effect of stack area. Total exhaust-stack length, 14 in.; engine rpm, 2550; restriction at exit; fuel/air, .085.

W-43

W-43

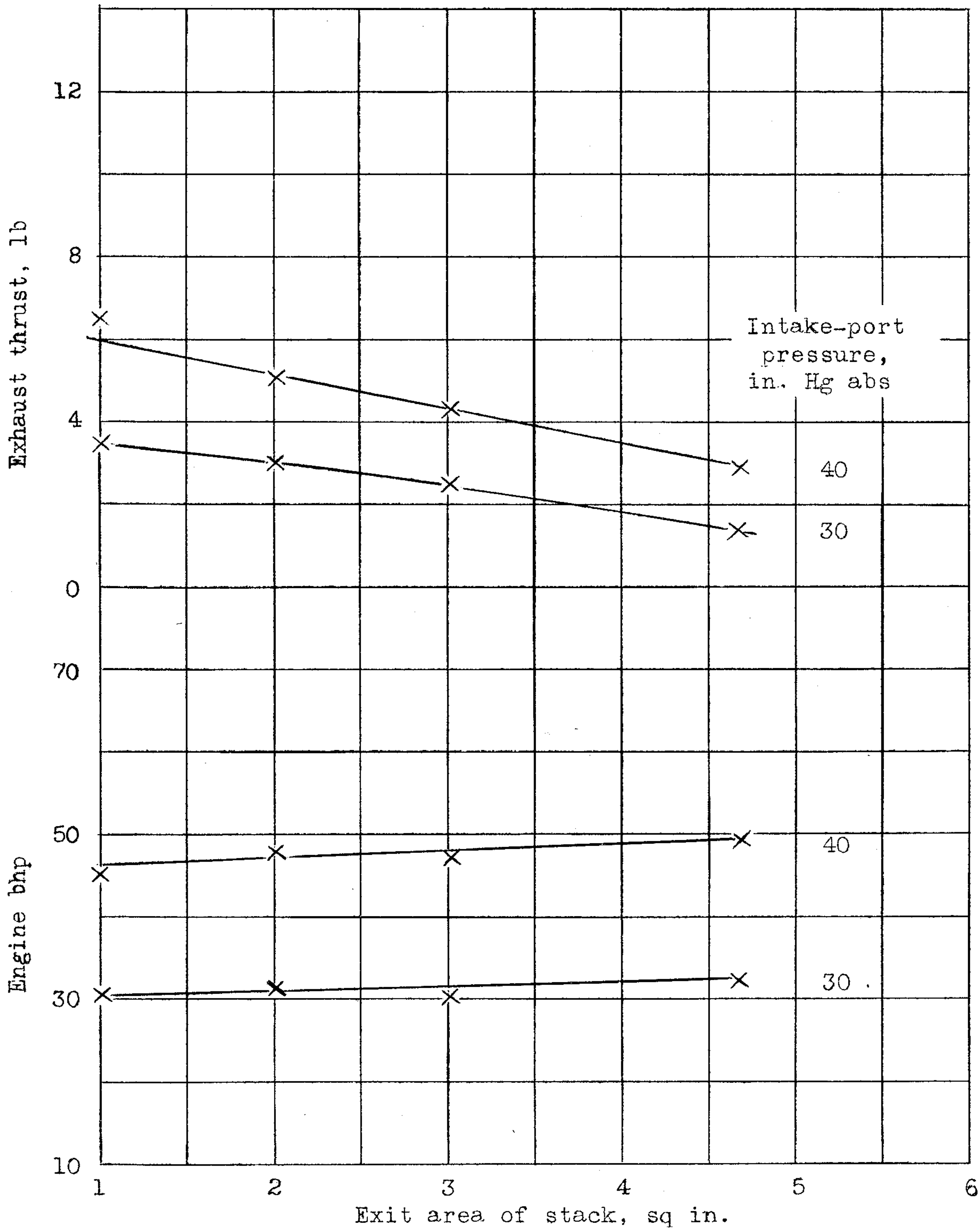


Figure 5.- Effect of stack area. Total exhaust-stack length, 14 in.; engine rpm, 1500; restriction at exit; fuel/air, .065.

W-43

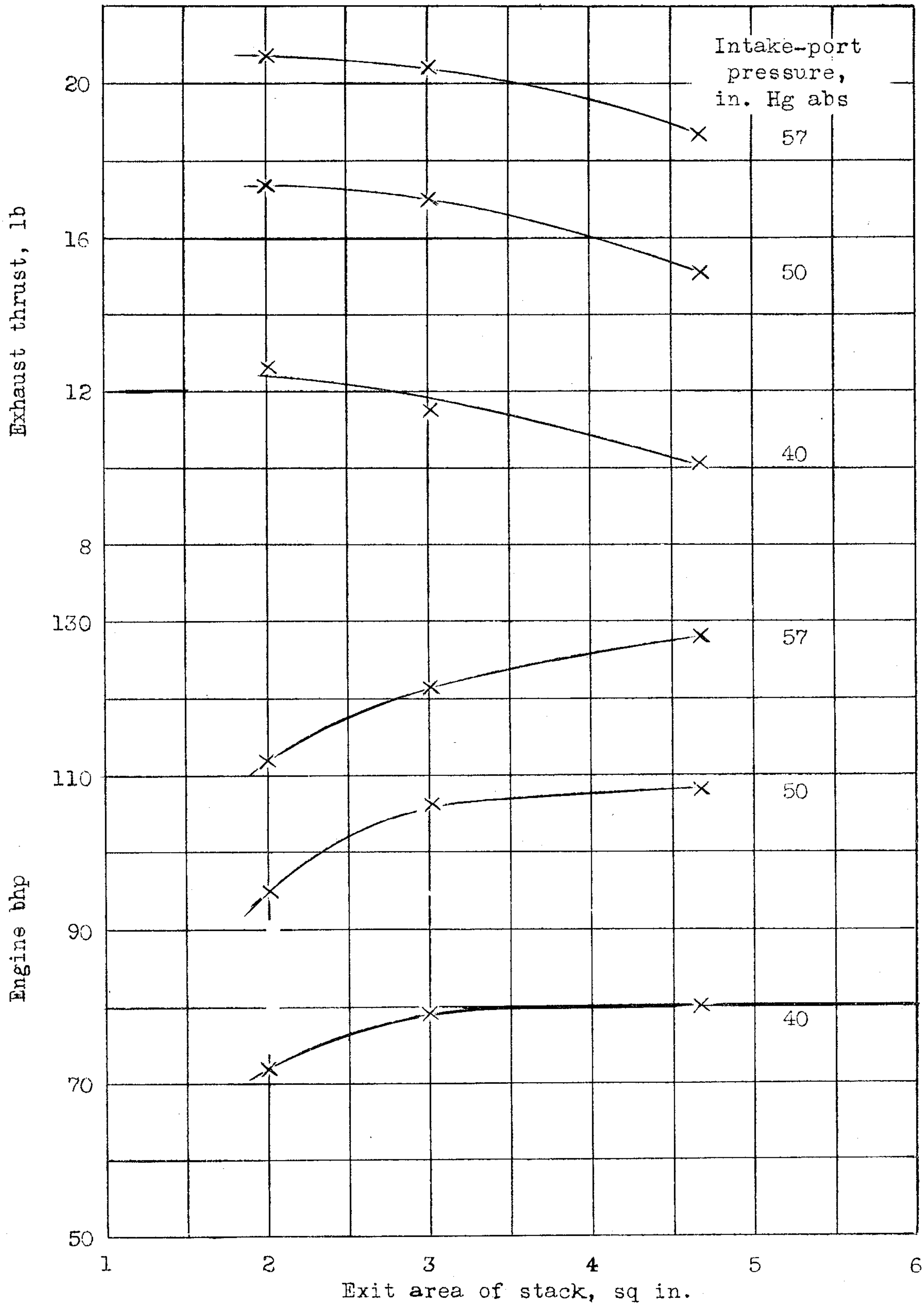


Figure 6.- Effect of stack area. Total exhaust-stack length, 33 in.; engine rpm, 2700; restriction at exit; fuel/air, .085.

W-43

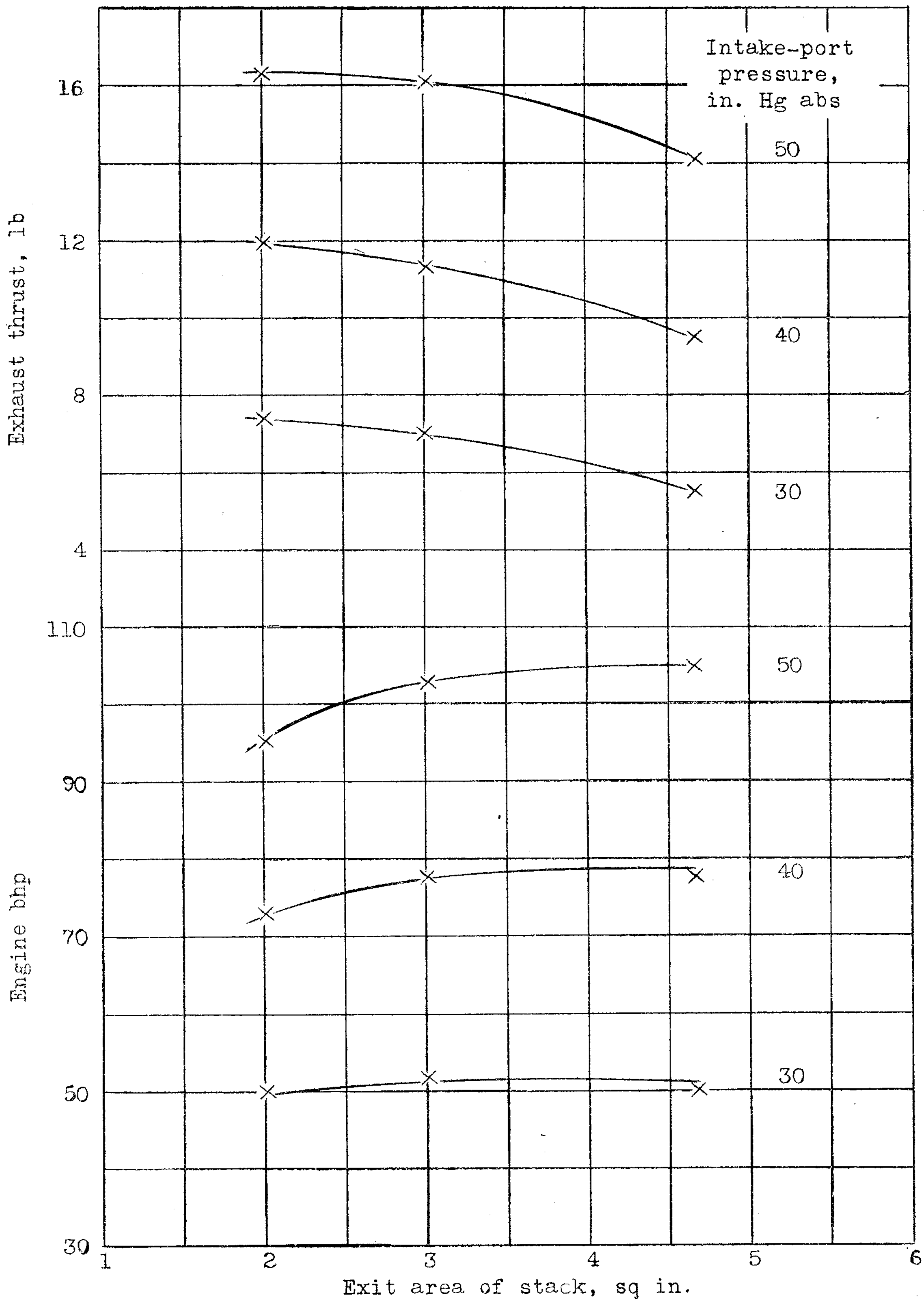


Figure 7.- Effect of stack area. Total exhaust-stack length, 33 in.; engine rpm, 2550; restriction at exit; fuel/air, .085.

W-43

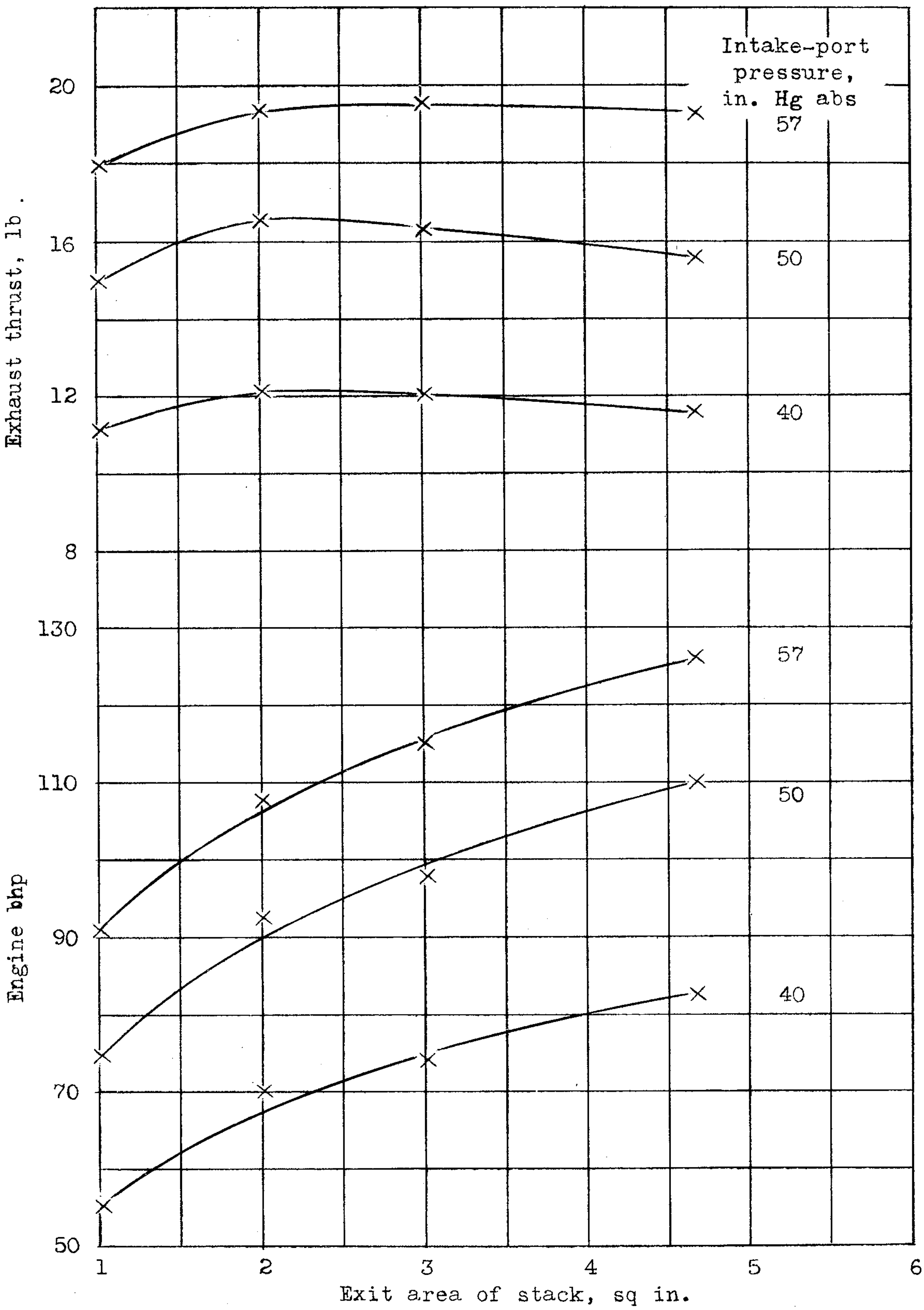


Figure 8.- Effect of stack area. Total exhaust-stack length, 50 in.; engine rpm, 2700; restriction at exit; fuel/air, .085.

W-43

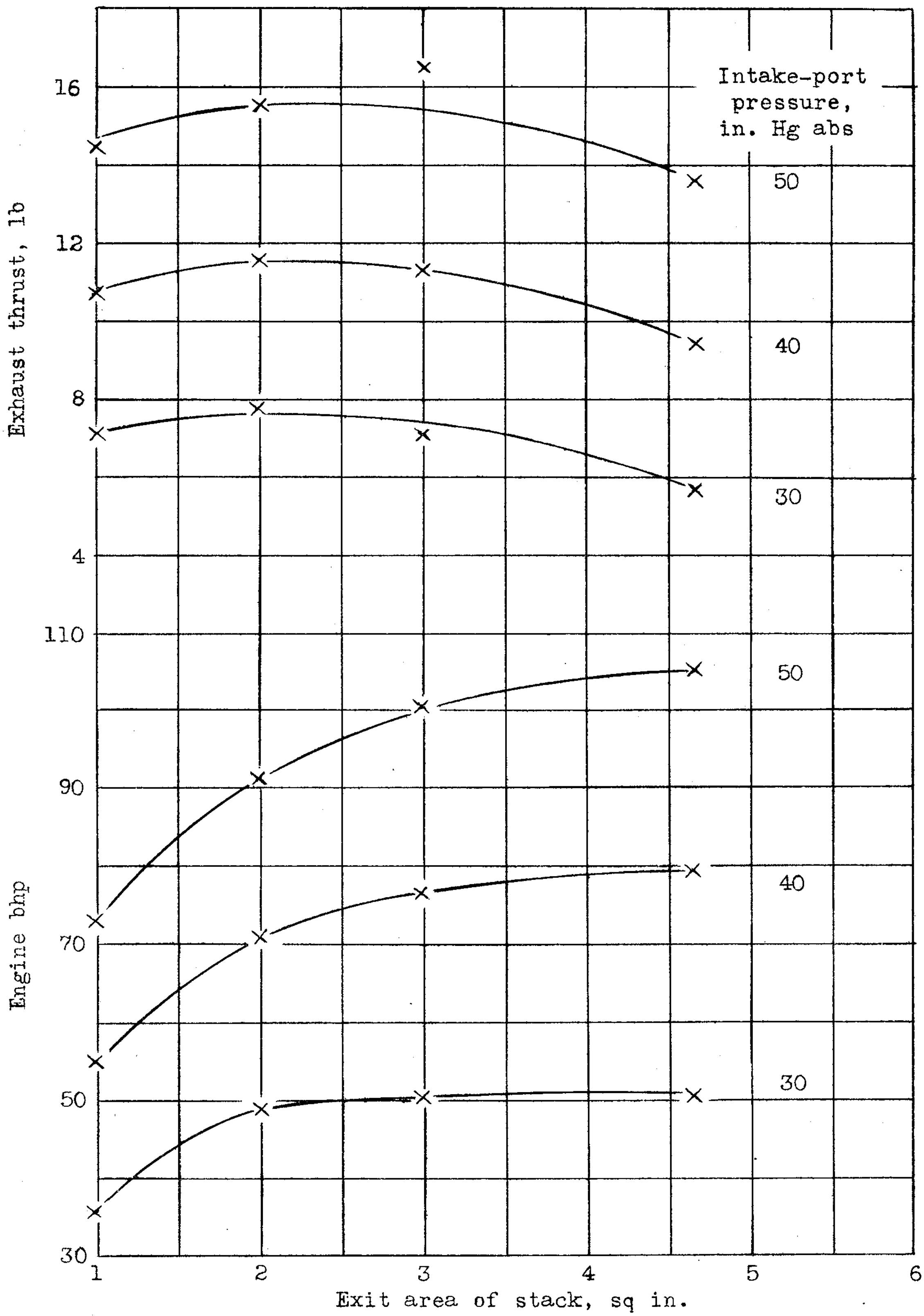


Figure 9.- Effect of stack area. Total exhaust-stack length, 50 in.; engine rpm, 2550; restriction at exit; fuel/air, .085.

W-43

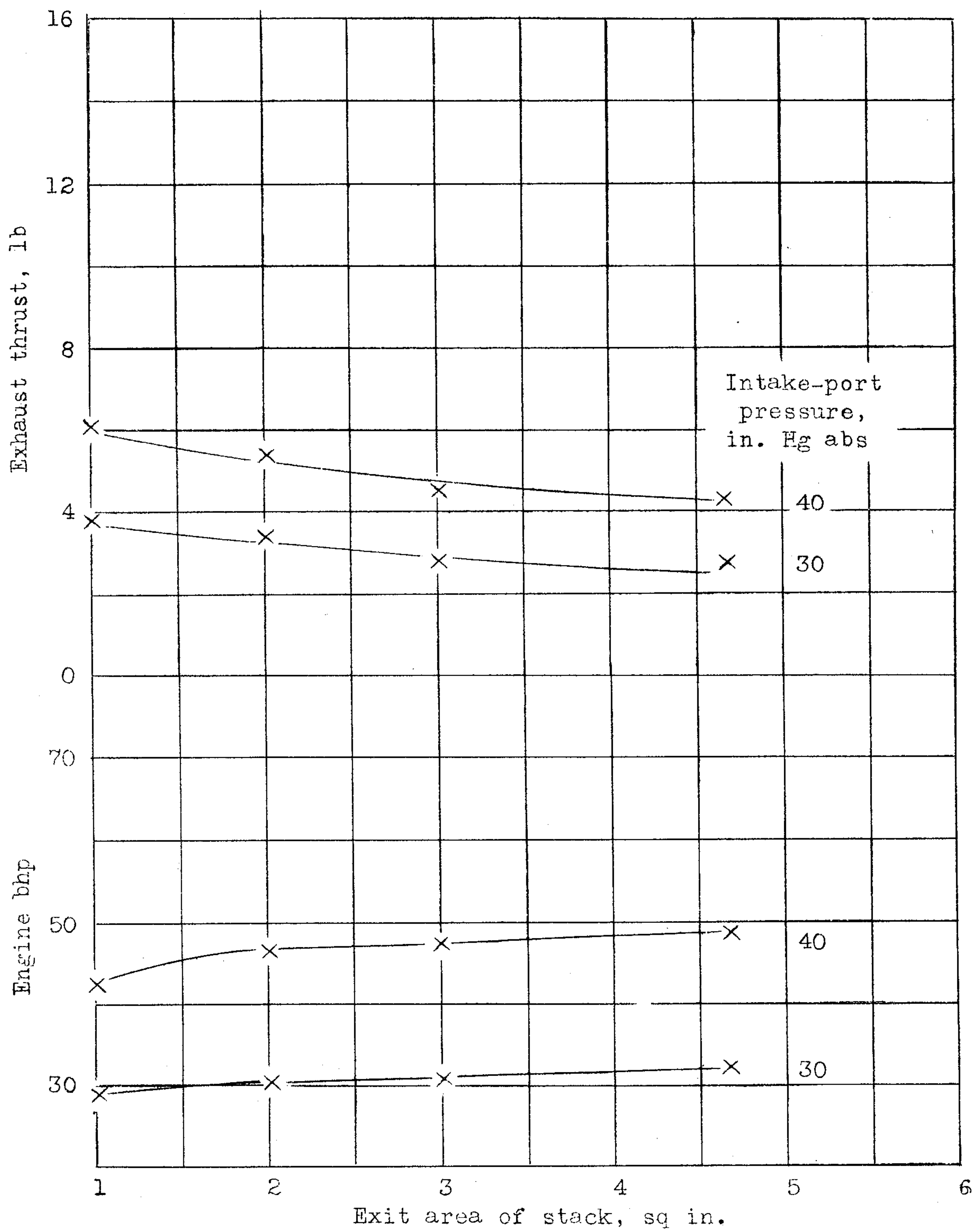


Figure 10.- Effect of stack area. Total exhaust-stack length, 50 in.; engine rpm, 1500; restriction at exit; fuel/air, .065.

W-43

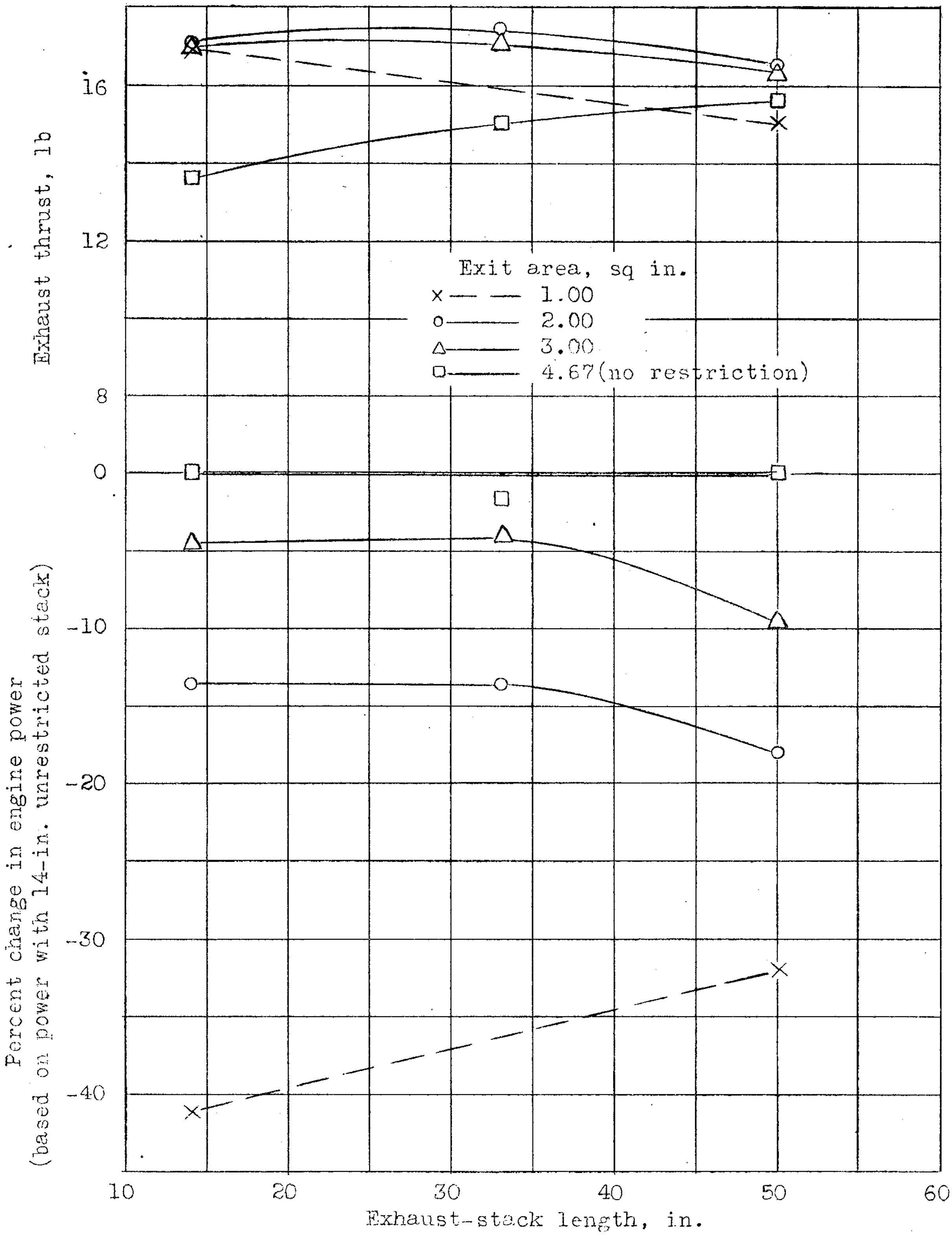


Figure 11.- Effect of stack length. Engine rpm, 2700; intake-port pressure, 50 in. Hg abs; restriction at exit; fuel/air, .085

W-43

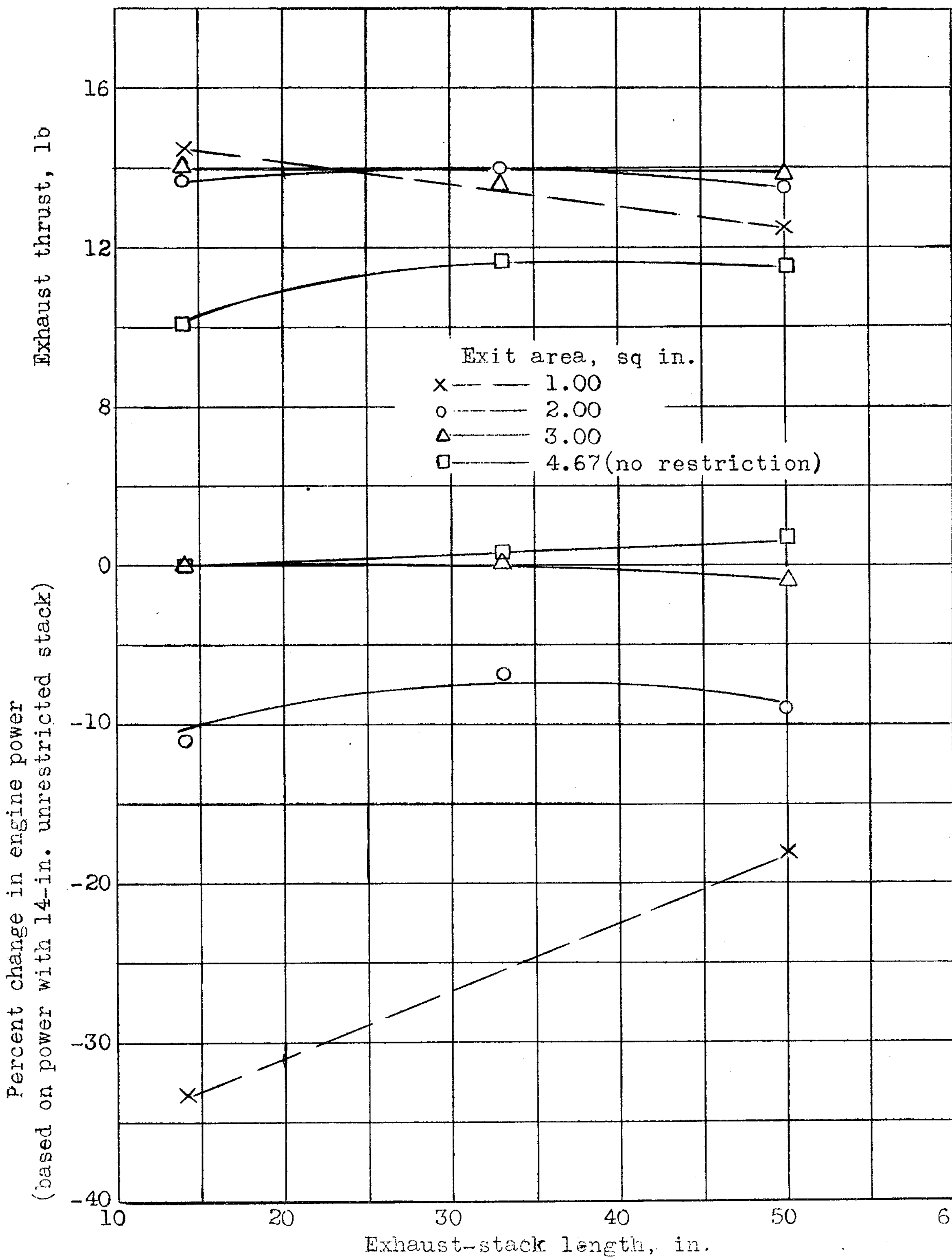


Figure 12.- Effect of stack length. Engine rpm, 2550; intake-port pressure, 45 in. Hg abs; restriction at exit; fuel/air, .085.

FIG. 13.-TESTS OF VARIOUS SHAPES OF EXHAUST STACKS
2700 RPM
.085 F/A

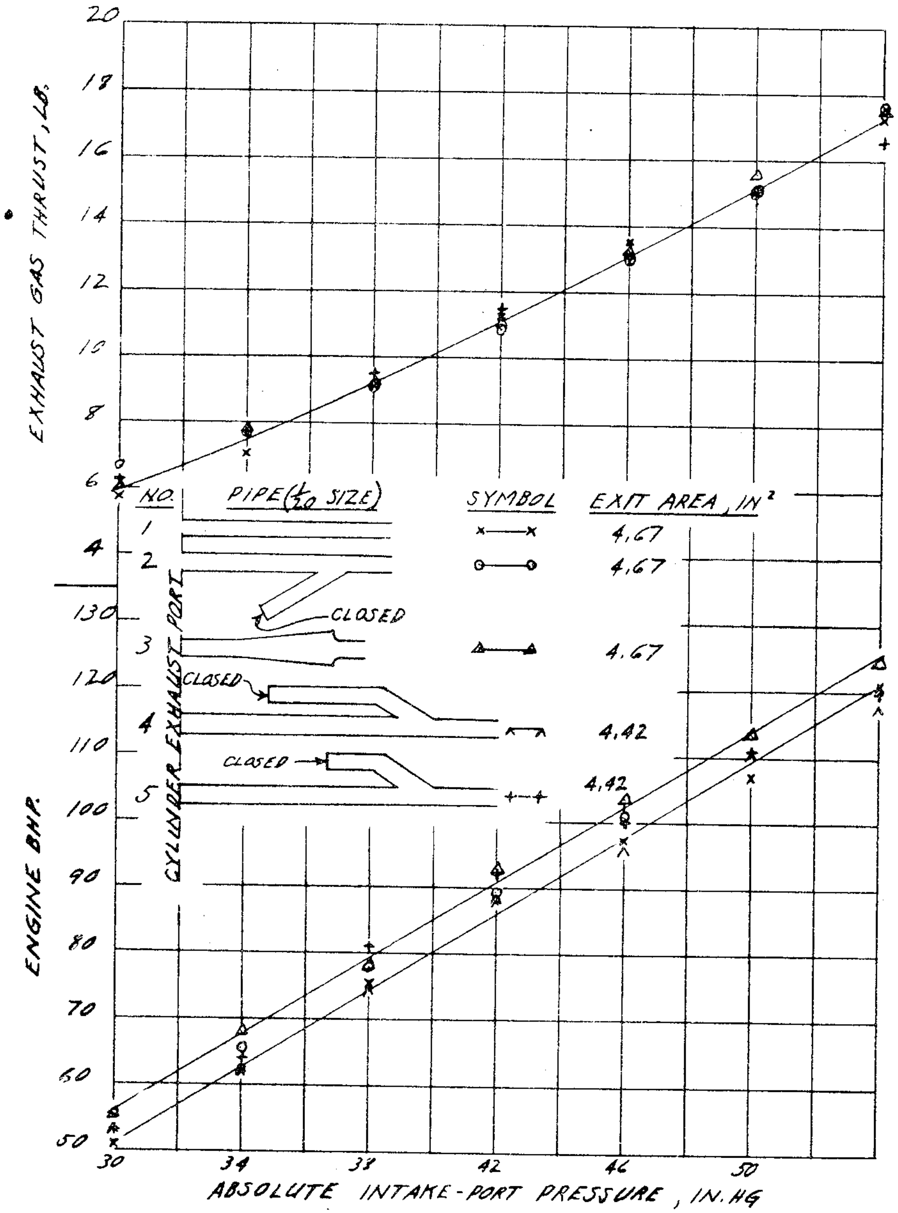
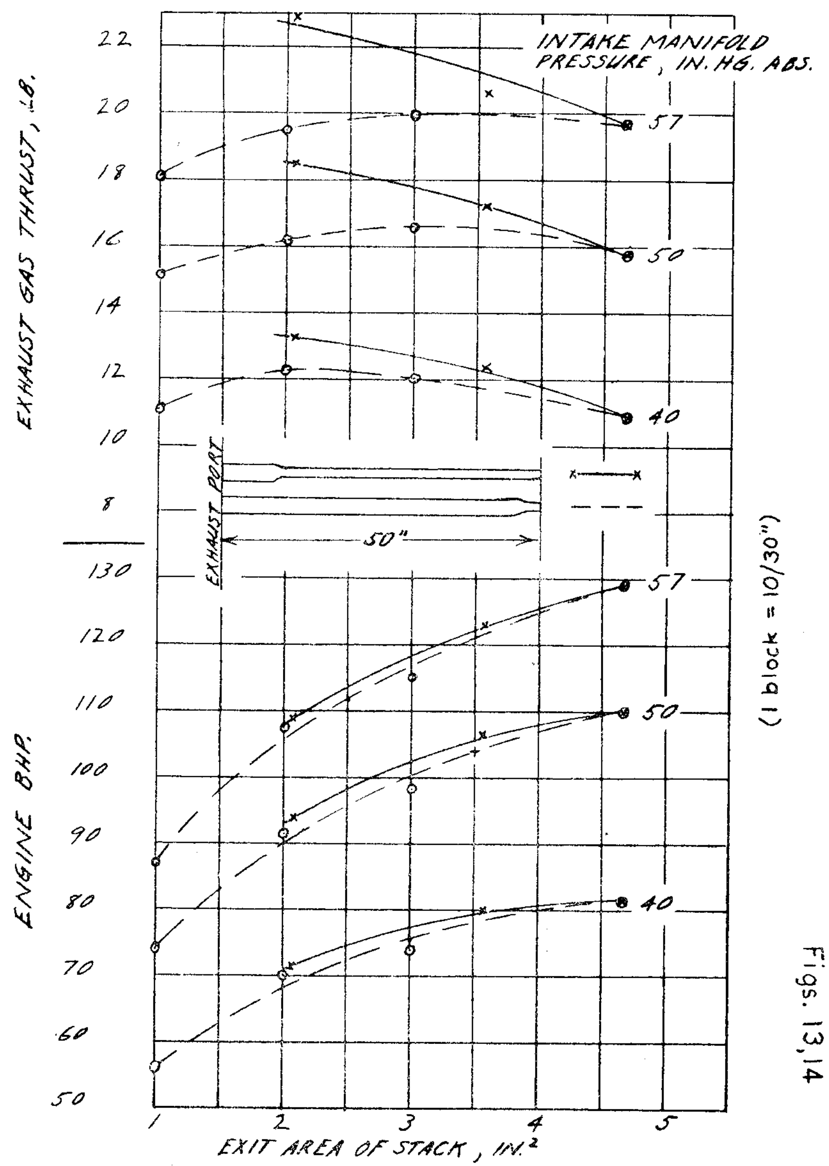


FIG. 14.-TESTS OF LONG-THROAT NOZZLES
TOTAL EXHAUST-STACK LENGTH - 50"
ENGINE RPM. 2700
SOLID LINES - RESTRICTION 8¾" FROM CYLINDER
DASH LINES - RESTRICTION 45" FROM CYLINDER



(1 block = 10/30")

Fig. 15. - Water Injection Run

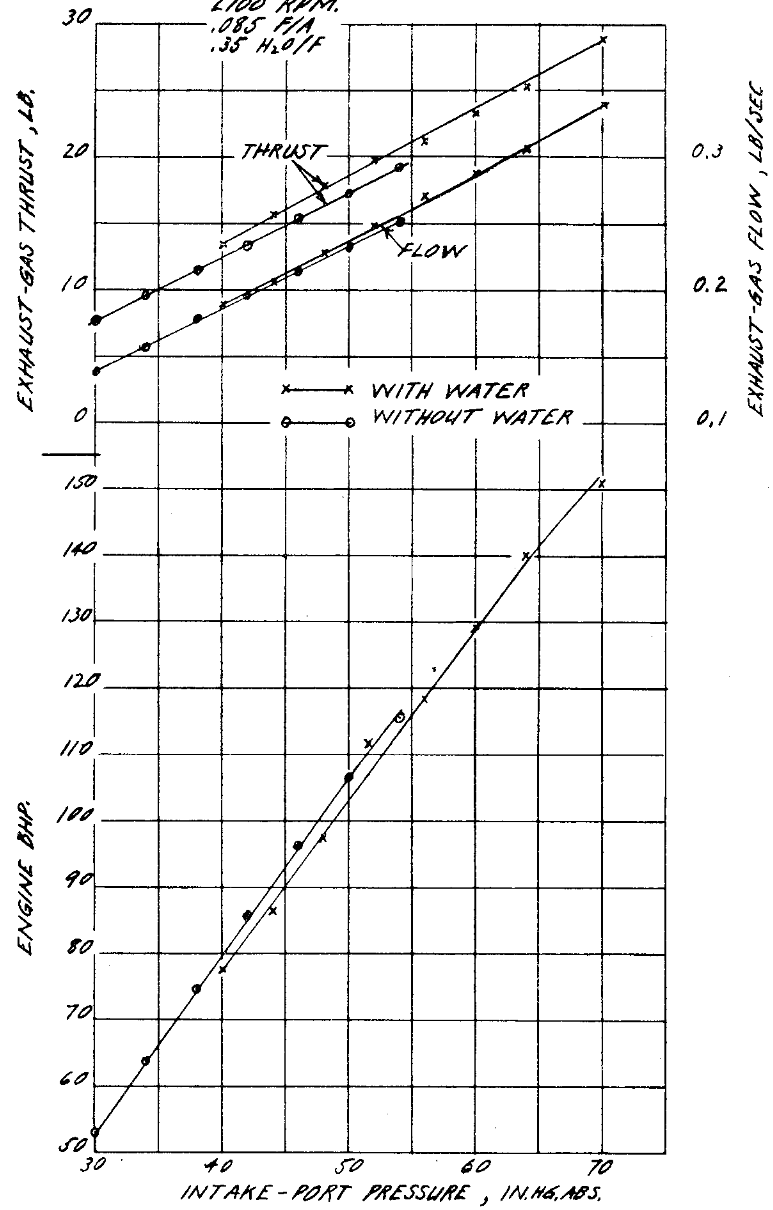
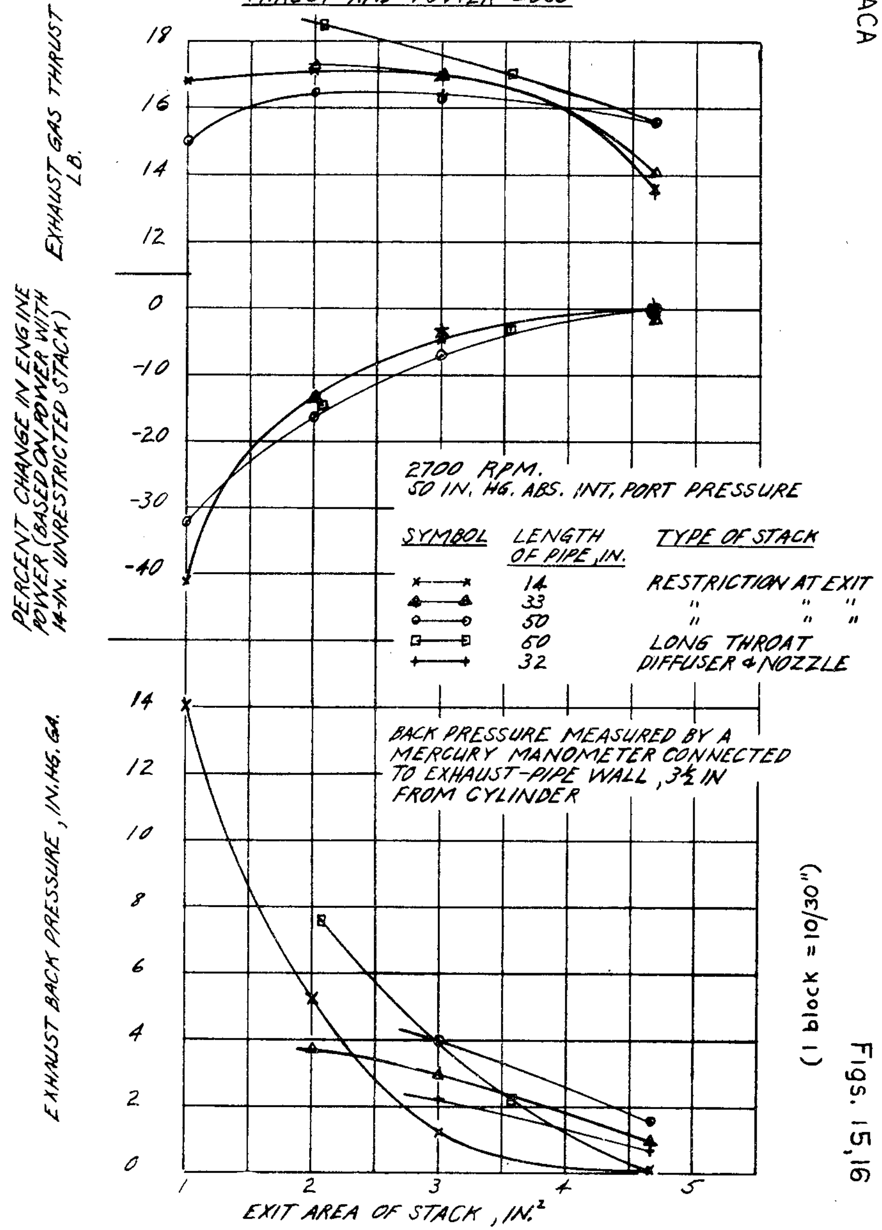


Fig. 16. - Comparison of Exhaust Back Pressure with Thrust and Power Loss



(1 block = 10/30")

NACA

Figs. 15,16

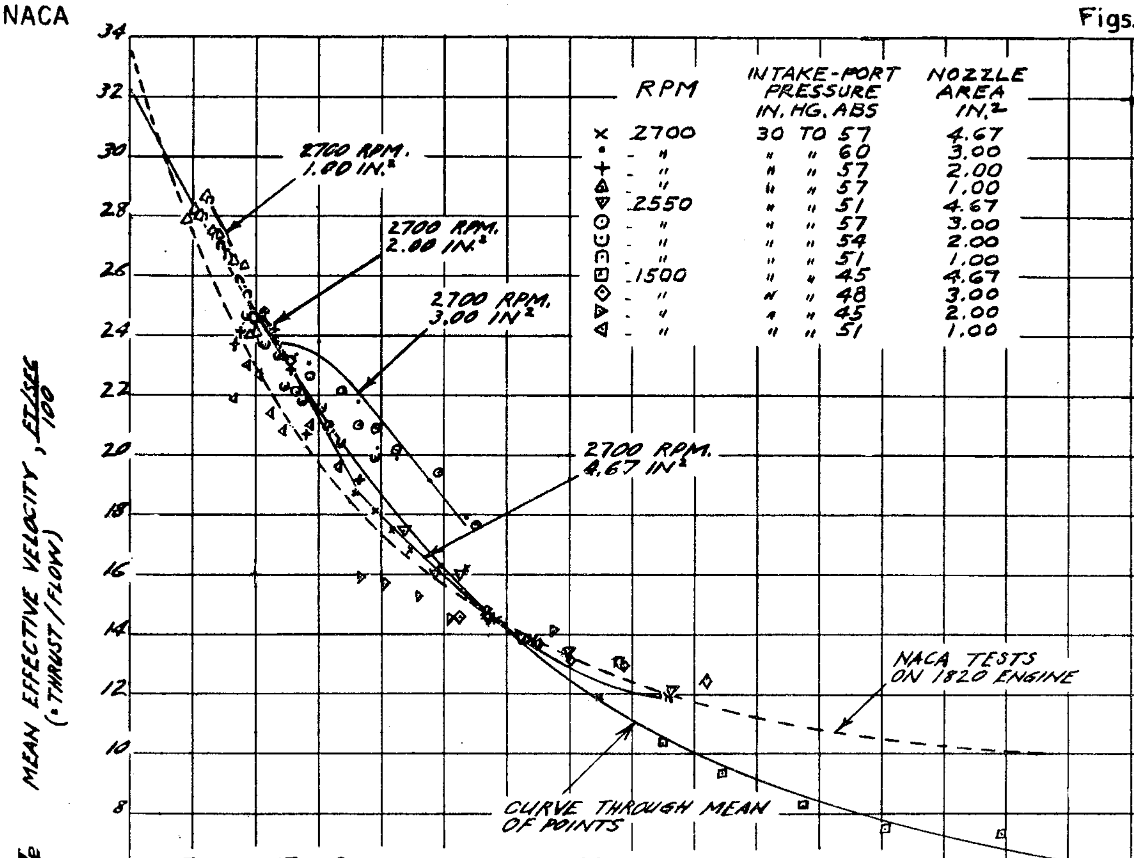


FIGURE 17.- COMPARISON WITH NACA DATA ON 1820-ENGINE. TOTAL EXHAUST STACK LENGTH 14 IN. RESTRICTION AT EXIT.

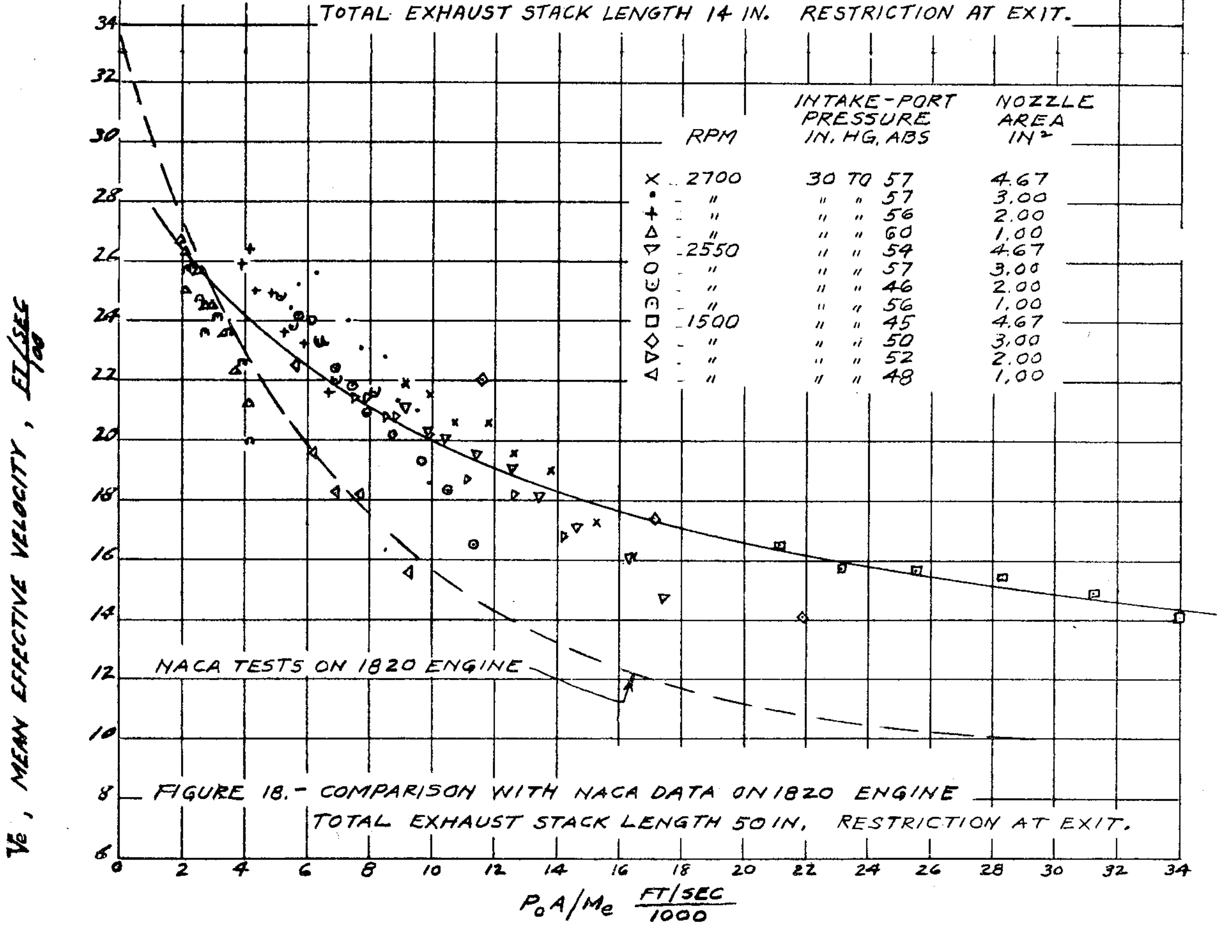


FIGURE 18.- COMPARISON WITH NACA DATA ON 1820 ENGINE TOTAL EXHAUST STACK LENGTH 50 IN, RESTRICTION AT EXIT.

W-43